# Multi-wavelength Optical Add-Drop Multiplexer with Nanosecond Reconfiguration Times for Local Area Networking

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## ABSTRACT

It is desirable for data networks to have low transmission latency. This may be achieved by exploiting the short packet lengths and the high bandwidths that can be achieved using multi-wavelength operation. Semiconductor optical amplifiers (SOAs) have been demonstrated as building blocks for optical switches and have also been shown to be well suited to the fast switching required for optical packet switching [1]. We have realised an InP based add-drop multiplexer (ADM) integrated on a single 850 µm x 850 µm chip. The bit error penalty performance has previously been shown to be below 1.2 dB for each of the operating paths through the device: add, drop and through modes at 2.5 Gbit/s data rates. Further, low penalty operation has previously been demonstrated experimentally with 4 simultaneous wavelengths [2].

It is known that the dynamic range of an SOA can limit the number of wavelengths supported and that the pattern sensitivity in SOAs increases their operating penalty [3]. We investigate the multi-wavelength operation of our ADM device and show that a power penalty of less than 0.8 dB is maintained over a 20 dB input power dynamic range. We also show a –3 dB optical bandwidth of 30 nm suitable for multi-wavelength operation of cascaded ADMs. Finally we present experimental results to show that the pattern dependent operating penalty of the ADM is reduced as the number of wavelengths of asynchronous data is increased. This result may be exploited in our proposed optical data network to produce an improved optical penalty.

Key words: SOA, WDM, penalty, dynamic range, pattern sensitivity

## 1. INTRODUCTION

Many optical packet switching schemes have been reported [4], typically these have been developed with telecommunication network requirements in mind and include features such as high levels of redundancy, coarse switching granularities and complex optical processing. Data communications links, in contrast, require low cost, low power solutions with low transmission latency [5]. The low transmission latency desirable for local data networks may be achieved by exploiting short packet lengths and the high bandwidths that are possible if multiple wavelengths are used. We have previously proposed a wavelength striped, slotted protocol suitable for data networks [5]. Features of this protocol relevant to the performance of the ADM are described in section 2 of this paper.

Switching short packet lengths with good transmission efficiency requires switching on nanosecond timescales. This requirement limits the range of technologies suitable for packet switching. Many technologies such as Liquid Crystal (LC) and Micro Electro-Mechanical Systems (MEMS) have been used for optical packet switching, however in general these technologies have switching times in excess of 1 µs. Fast optical switching technologies, such as electro-optic modulators, have also been proposed for use in optical packet switching; however electro-absorption modulators exhibit significant optical absorption in the 'on' state. This restricts their use as elements for scalable optical switches because the optical insertion losses accumulate as optical switches are scaled to larger port counts. Semiconductor optical amplifiers (SOAs) have been proposed for their use in optical switches and have been shown to be well suited to fast switching [6]. The inherent gain in SOAs makes them well suited to compensating for optical insertion losses due to optical splitting that accumulates with high switch port counts. The wide band operation and good extinction ratios of SOAs are also well suited to multi-wavelength optical packet switching.

The bit error penalty performance of our ADM device has been presented previously [2]. In this paper, the multi-wavelength performance of this ADM is studied with an emphasis on tailoring the proposed transmission protocol for optimum performance with this device. In particular, the number of possible wavelengths and the scalability of the port count of switch are considered.

## 2. DATA NETWORKING

The ADM device is considered here for use in a data networking application, from which the necessary operating requirements are found.

### 2.1 Optical packet switching in data networks

Two key technologies have come to dominate the physical layer of networking - in wide area networks, meshed IP/SONET routing prevails and in LANs, Ethernet predominates. Switching, in these technologies, continues to be performed in the electrical domain. While many systems have been proposed that move packet switching to the optical domain, [4] none of these have yet proved to be commercially successful. Optical packet switching offers potential cost savings over traditional electrically switched technologies by eliminating optical-to-electrical transceivers at each switching port. This becomes a significant saving if a high port count switch is implemented. Also as transmission rates exceed 10 Gbit/s, the required multi-wavelength operation also results in a high transceiver count. Optical switching offers the additional benefit of reduced power consumption in comparison to equivalent electrical switches.

### 2.2 Buffering and latency

The latency of a data network can be defined as the time delay between the launch of a packet and its arrival. End-to-end latency of a network includes contributions from both transmission and buffering latencies. Ideally transmission latencies should be kept as low as possible in data networks. Transmission latency may be minimised by increasing the transmission rate and buffering latency may be reduced with the use of short packets.

Wide area networks are inherently meshed multi-hop networks. If data is to remain in the optical domain, this leads to a requirement for optical buffering to resolve the contention caused by packets arriving from multiple destinations simultaneously. The need for optical contention resolution can be eliminated in data networks if single hop optical switches can be implemented. In such data networks, the data source will typically include considerable processing power; it is therefore possible to cheaply implement contention resolution in the electrical domain before launch into the optical domain. This data 'smoothing' at the edge of the network eliminates the requirement for costly and complex optical buffering.

| | | Effect | Description |
|---|---|---|---|
| Jitter | $t_o$ | 30ps/km/C | Temperature dependant change |
| | | 80ps | Transmitter jitter |
| | | << $t_s$ | Switch jitter |
| | $t_j$ | $t_o$ * 2 | Slot phase lock accuracy |
| Skew | $t_s$ | 5ns | Guard time for optical switch |
| | $t_\lambda$ | 1ns/km/50nm | Chromatic dispersion at 1550nm |
| | $t_c$ | 80ps + few bits | Clock recovery |

*Table 1: typical time slot timing parameters*

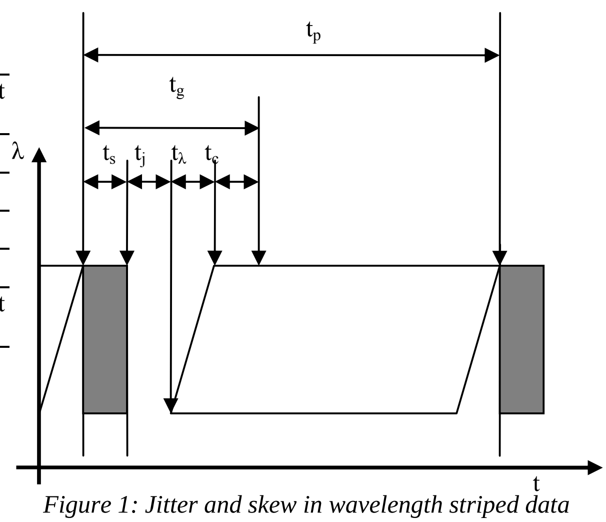


*Figure 1: Jitter and skew in wavelength striped data*

### 2.3 Wavelength striping

In contrast to conventional WDM, in which each wavelength is individually switched, a wavelength striped coding scheme is proposed. In this format, the bits forming a word are launched simultaneously on different wavelengths. Also known as "optical bus" [7] and bit parallel WDM [8], we refer to this as wavelength striping. Figure 1 shows the format of a wavelength striped timeslot in a semi-synchronous optical network composed of point-to-point links and a central switch scalable to N ports. Wavelengths are depicted on the vertical axis and time in the horizontal axis. Guard bands ($t_s$) allow for outage during switching and jitter and dispersion skew on the optical path. Table 1 illustrates typical values of the various timing parameters that have an impact on the design. In the small scale network under consideration, polarization and chromatic dispersion can be neglected, while material dispersion and temperature effects are pronounced [4].

Based on the data format in this proposed data network, we can extract the implied optical switching performance requirements. Switching times of the order of a few nanoseconds are required to ensure good transmission efficiency. Loss-less fibre-to-fibre operation is required for operation without external optical amplifiers. Sufficient optical bandwidth for multi-wavelength operation centered on 1550 nm is necessary. The extinction ratio must be sufficient to prevent crosstalk. The port count must be scalable without increasing the optical attenuation through the switch.

## 3. FAST SWITCHING WITH SOAS

### 3.1 Switching characteristics

The population inversion time in an SOA limits its turn on time. Typically carrier lifetimes will be of the order of hundreds of picoseconds. In practice the turn on time of an SOA switch is additionally limited by the slew rate of the current driver used to control the SOA. Switching times of less than 1 ns have been reported; however power consumption requirements of the drive electronics may require slower switching times [9].

### 3.1 Pattern sensitivity in SOAs

Near saturation, operation of an SOA results in pattern dependent distortion. During a string of consecutive 'zeros', the population inversion builds up and the gain is increased temporarily on the subsequent 'one'. This results in increased distortion and a higher penalty. Figure 2 shows the results of simulation of a 10Gbit/s data pattern '1010001110' amplified through a single SOA operating near saturation. The X-axis shown simulation time samples (5 samples per picosecond) and the Y axis is optical output level. These results show that the gain distortion varies with the number of preceding zeros. A 4 dBm power spike is observed after one zero bit and this increases to 7 dBm after three consecutive zeros.

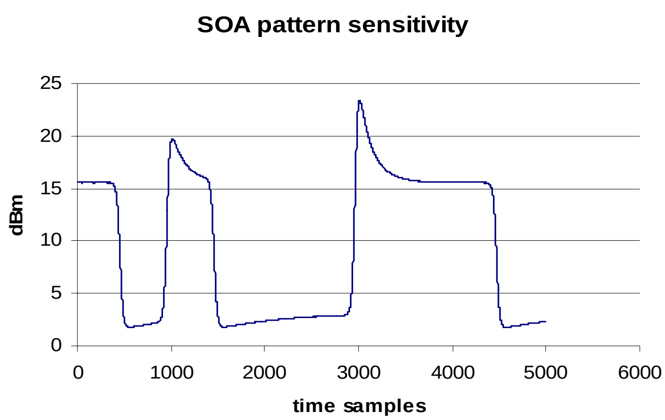


*Figure 2: Pattern dependent distortion*

Typically, pattern sensitivity can be reduced by operating the SOA in the near linear region of operation. The disadvantage of this solution is that it limits the operating input power dynamic range (IPDR). Another solution is to implement gain clamping. The aim of gain clamping is to clamp the carrier concentration to a fixed level and hence

eliminate population inversion build up during long strings of zeros. Gain clamping can be achieved by appending small Bragg grating mirrors to the ends of the SOA. If the grating is set so that the lasing wavelength is outside the wavelength of the desired gain region, the gain at the operating wavelength will remain constant for a larger range of input powers. A disadvantage of gain clamping is that it results in reduced optical gain.

The solution that we consider in this paper is to use a line coding scheme to limit the worst case run of zeros. In data networks, line coding is typically used to aid clock recovery and ensure DC balance. For example on a single wavelength 8B10B coding is used in Gigabit Ethernet to reduce the worst-case run length of consecutive 'zeros' to 4 in data or 5 in the case of 8B10B control sequences. Line coding has the advantage of being cheap to implement, however the downside is reduced bandwidth efficiency as in 8B10B 10 bits are required to transmit one octet of data. If line coding is used in conjunction with asynchronous multi-wavelength data, a further improvement in pattern sensitivity is achieved. We present experimental to demonstrate this.

### 3.2 Cross gain modulation

If a modulated optical signal is applied to an SOA, when high output powers are generated the gain will fall. This gain compression is caused because the rate of stimulated recombination is higher than the replacement carrier injection rate. Thus in multi-wavelength operation of an SOA, as one wavelength is modulated from the 'off' to the 'on' state, the gain available at other wavelengths and hence their output power will fall. This effect is known as cross gain modulation (XGM). Several solutions have been suggested to this problem. Operation below saturation in the near-linear region results in a minimal gain variation as the aggregate input power varies. A disadvantage of this method is that since the SOA must be operated at lower input power the SNR performance will be degraded. Gain clamping has also been studied as solution to cross gain modulation [10]. As with pattern sensitivity, the optical power averaging obtained through the use of asynchronous multi-wavelength data offers the possibility of reduced XGM.

### 3.3 IPDR and multi-wavelength operation

In an SOA, the power penalty will vary over a limited range of input optical powers. If the input power is too low or too high, the power penalty will increase. This is referred to as the IPDR. IPDR for individual SOAs of greater than 20 dB has been reported, however, little improvement of IPDR is reported with the use of gain clamping [11].

## 4. ADD-DROP MULTIPLEXER

We have realised an InP based add-drop multiplexer (ADM) comprised of a grid of eight separately addressed semiconductor optical amplifiers integrated on a single 850 µm x 850 µm chip [2]. Figure 1 shows the device topology. Three modes of operation are supported – ring 'add', ring 'drop' and ring 'through'. These operating modes are generated by biasing appropriate sections of the SOA waveguides. The 'through' operation mode has been designed to pass packets around a ring. The 'add' mode has been designed to add packets into a ring. The 'drop' mode has been designed to drop packets from a ring. In addition, the 'through' mode also supports a loop-back on the user side for signal continuity at each network interface.

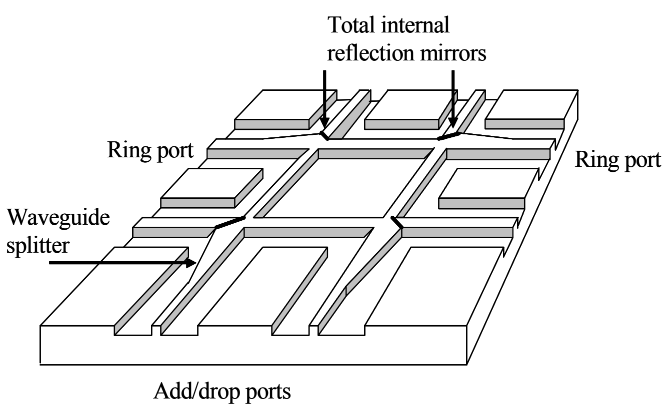


*Figure 3: Schematic diagram of ADM*

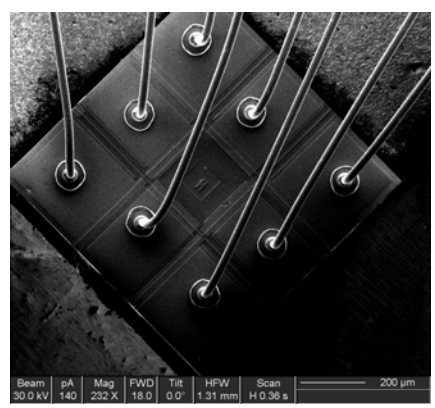


*Figure 4: Focused ion beam image of ADM*

Matched path lengths allow path independent gain, and short amplifier lengths reduce power consumption and ensure compact dimensions. The waveguide separation of 250 µm is well suited to ribbon fibre coupling. The input guides expand to 1 x 2 splitters that incorporate 45º totally internal reflecting mirrors prior to two perpendicular amplifying gates (Fig. 1). The ring 'through' ports are anti-reflection coated to 0.21% and the add/drop ports remain as cleaved.

The epitaxial design and ridge waveguide fabrication technology used is common to laser diode fabrication, although multiple p-side electrodes with isolation of the order of 600 Ω are also defined. The total internal reflection mirrors are etched subsequent to bonding using focused ion beam etching.

## 5. EXPERIMENTAL SETUP

Figure 5 shows the setup used for penalty and IPDR measurements. The electrical PRBS signal from the HP BERT is used to drive the electro-absorption modulators integrated into the cooled DFB lasers. The lasers wavelengths are centred at 1550 nm with 200 GHz spacing. TE polarisation is maintained at the input of the ADMs using polarisation controllers (not shown in diagram). Wavelength multiplexing is performed with the used of a planar waveguide AWG. The optical power of each wavelength is set to the same level by controlling the bias current of each laser. The net optical signal power is controlled by setting the EDFA gain. The optical power is monitored using 90/10 couplers at two reference points – at the input to the optical switch and at the input the PIN photo diode. The optical switch is temperature controlled and all SOAs are 50 ohm terminated. A variable DC voltage source is used to control SOA bias.

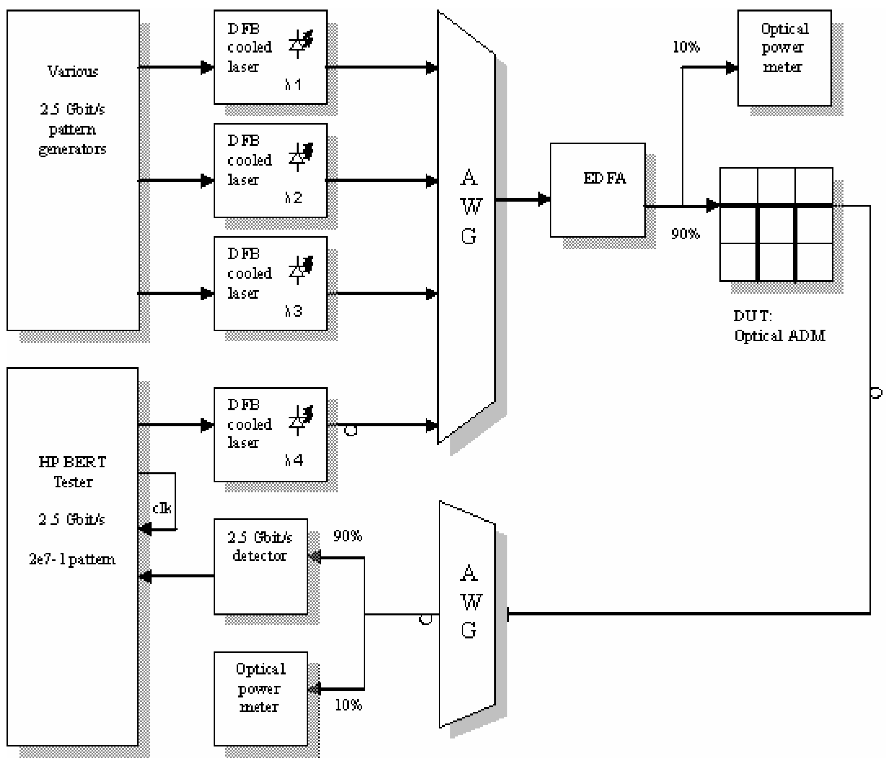


*Figure 5: Setup for penalty and IPDR measurements*

The ADM is mounted on an optical bench and the optical signal is coupled onto the waveguide using fibre lenses. The coupling loss at each facet is estimated at around 10 dB. This high loss is believed to be due to spot size or shape mismatch between the waveguide and the fibre. In the 'on' state each individually addressable SOA gate in the ADM bias is set to 26 mA. In the 'off' state zero bias current is set.

## 6. RESULTS

Figure 6 shows the gain curve of the 'through' path of the ADM. Saturation is measured at an input power of 10 dBm at the fibre. The net gain includes 6 dB of coupling losses from the two integrated power splitters and the coupling losses in and out of the ADM. If the coupling losses are taken into account, the net on chip gain below saturation is better than +10 dBm.

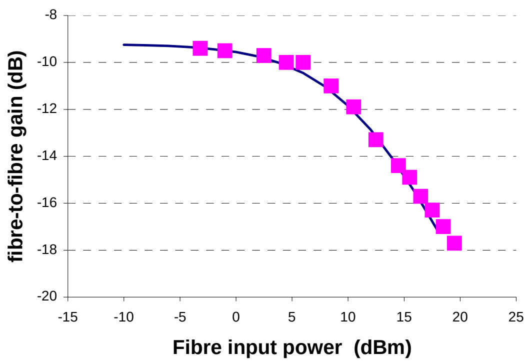


*Figure 6: ADM gain curve*

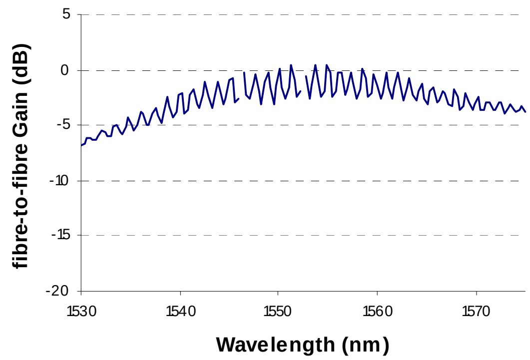


*Figure 7: ADM gain spectrum*

Figure 7 shows a 30 nm operating spectrum of with 3 dB gain drop at 1540 nm and 1570 nm. The net fibre-to-fibre loss of ~2 dB is due to the coupling losses into the device. For these results each gate in the ADM is driven with 30 mA leading to a near zero fibre-to-fibre gain. However this high gain results in peak-to-peak ripple of 2.5 dB in the wavelength response due to the Fabry Perot cavity modes. These are caused by imperfect anti-reflection coatings (0.21%).

The device power penalty is measured as the difference between the optical receive power with a BER of $10^{-9}$ with the ADM present compared to the optical power at the detector with same BER but without the ADM present. For optimal penalty results these measurements are performed with 26 mA bias on each of the SOA gates. The power penalty of the 'through', 'add' and 'drop' paths are summarised by wavelength and path in table 2. For the 'through' path, penalties from 0.0 - 0.3 dB are measured. The penalties degrade, however, on both the 'add' and 'drop' paths. This is attributable to the lack of antireflection coating on the add-drop ports which leads to a gain ripple of order 2 dB for the operating regime. In contrast, the 'through' path exhibits a negligible gain ripple at this bias current.

| | Through | Add | Drop |
|---|---|---|---|
| $\lambda 1$ | 0.0 dB | 0.6 dB | 0.4 dB |
| $\lambda 2$ | 0.3 dB | 0.4 dB | 0.8 dB |
| $\lambda 3$ | 0.0 dB | 0.5 dB | 0.9 dB |
| $\lambda 4$ | 0.2 dB | 1.2 dB | 0.8 dB |

*Table 2: Error penalties at $10^{-9}$ for 'through', 'add' and 'drop' paths.*

Figure 8 shows the relationship between the data pattern, number of wavelengths and ADM power penalty. For these measurements we have operated the ADM closer to saturation in order to accentuate the pattern dependent penalty. Several different patterns types were used. $2^4$-1 PRBS (with a worst-case run of four zeros), $2^7$-1 PRBS (with a worst-case run of seven zeros) and $2^9$-1 PRBS (with a worst-case run of nine zeros). The ADM's penalty is shown to increase as the PRBS pattern length increases. This is consistent with the expected pattern sensitive behaviour of SOAs. Interestingly, the results also show a drop in the penalty as the number of wavelengths is increased. We believe that this is due to each optical signal being modulated with asynchronous data resulting in optical power averaging across all wavelengths. This power averaging results in a reduction of pattern dependent distortion as more wavelengths are

added. In order to gain the full benefit of power averaging, the use of both line coding and asynchronous data are required. Because both of these features are fundamental to our data networking proposal, we can see that multi-wavelength operation will automatically be of benefit to the systems performance.

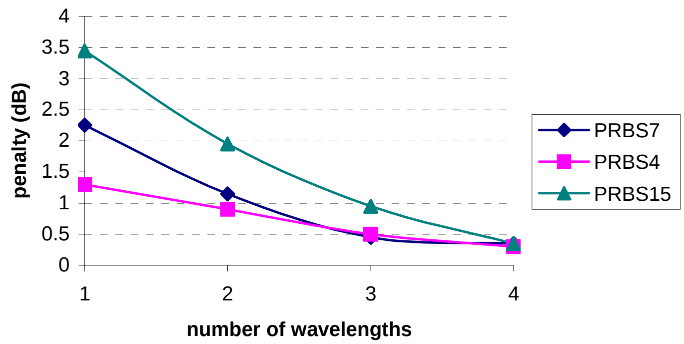


*Figure 8: Penalty vs. number of wavelengths*

Figure 9 shows the measured relationship between the input power and the operating penalty of the ADM through path. Once the launch power exceeds +7 dBm, the operating penalty rises rapidly. No data for the low input power threshold was found as the receive power dropped below the minimum detector input power level. Based on ASE measurements at the receiver we expect that the lower limit to IPDR to be better than -20 dBm.

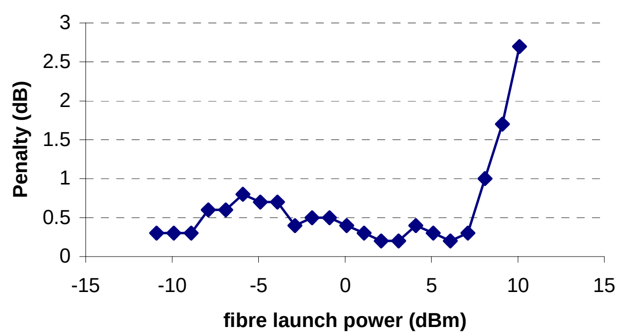


*Figure 9: ADM IPDR*

It is noted that the IPDR is an important parameter for multi-wavelength operation as the maximum number of wavelengths supported is limited by IPDR. The net optical power of all wavelengths must be lower than the upper IPDR limit and the optical power of each wavelength must be greater than the lower IPDR limit. The ratio of upper power limit to lower power limit thus limits the maximum number of wavelengths possible. This may become a design limit as the IPDR is reduced with cascaded devices [12].

## 6. CONCLUSION

We have shown that a power penalty of less than 0.8 dB is maintained over a 20 dB input power dynamic range and a -3 dB optical bandwidth of 30 nm. Modelling results are used to show the relationship between the pattern dependent distortion and the zero run length. We then demonstrate experimentally the possibility of multi-wavelength operation of our ADM. In particular we have shown that multi-wavelength operation with asynchronous data, works to the benefit rather than the detriment of the performance of our proposed data networking application for the ADM.

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